AD-A270 148

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b RESTRICTIVE MARKINGS
2a SECURITY CLASSIFICATION AUTHORITY N/A since Unclassified	3 DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release
2b DECLASSIFICATION/DOWNGRADING SCHEDULE N/A since Unclassified	
4 PERFORMING ORGANIZATION REPORT NUMBER(S)	5 MONITORING ORGANIZATION REPORT NUMBER(S)
6a NAME OF PERFORMING ORGANIZATION California Institute of Technology; 6b OFFICE SYMBOL (If applicable)	7a NAME OF MONITORING ORGANIZATION AFOSR/NL
6c ADDRESS (City, State and ZIP Code) 1201 E. California Blvd., 252-21 Pasadena, CA 91125	7b ADDRESS (City, State and ZIP Code) 110 Duncan Avenue Suite B115 Bolling AFB DC 20332-0001
8a NAME OF FUNDING/SPONSORING ORGANIZATION AFOSR/NL; 8b OFFICE SYMBOL (If applicable) NL	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER F49620-92-J-0432
8c ADDRESS (City, State and ZIP Code) 110 Duncan Avenue Suite B115 Bolling AFB DC 20332-0001	10 SOURCE OF FUNDING NOS PROGRAM ELEMENT NO. 61102F; PROJECT NO 2309; TASK NO AS; WORK UNIT NO
11 TITLE (Include Security Classification) Shock propagation in crustal rock	

12 PERSONAL AUTHOR(S)
Anderson, William W. and Ahrens, Thomas J.

13a TYPE OF REPORT	13b TIME COVERED	14 DATE OF REPORT (Yr., Mo., Day)	15 PAGE COUNT
Annual	FROM 920701 TO 930630	930908	

16 SUPPLEMENTARY NOTATION This work was sponsored by the Air Force Office of Scientific Research under 573 3600 293 47B1 612309 as 00000 61102F 503700 F03700.

17 COSATI CODES			18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB GR	

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

The shock Hugoniot and adiabatic release curves of sedimentary rocks display a range of different behaviors that affect the decay of shock waves propagating away from a confined source. Many of the minerals making up sandstones, shales, and limestones undergo phase transitions when shocked to pressures of interest to studies of coupling of energy from explosive sources into far field seismic waves. Both sandstones and limestones have been observed to exhibit elastic precursors and multiple wave behavior at shock velocities up to 3.7 km/s and 5.7 km/s, respectively [Ahrens and Gregson, 1964]. Hysteresis in the shock-release paths of materials results in irreversible energy deposition, thus depriving the shock wave of energy required to drive its propagation and resulting in a more rapid decay and less efficient coupling to far field waves than expected from geometrical effects alone. Thus, data constraining this behavior in rocks are essential for determining the cavity volumes for various degrees of decoupling for different lithologies.

The behavior of most sedimentary rocks during adiabatic release has not been experimentally investigated to a significant extent. Our objective was to obtain experimental data for shock and release behaviors of elastic and carbonate sedimentary rocks and use those data along with data from other sources, to develop a theoretical model of the hysteretic shock-release paths of these rocks. We use this model to constrain the energy deposited irreversibly in these rocks by the passage of shock and release waves. The release model we use is a modification of that used by Sekine et al. [1993, submitted] for granite.

93-23155

20 DISTRIBUTION/AVAILABILITY OF ABSTRACT	21 ABSTRACT SECURITY CLASSIFICATION
UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS ☐	UNCLASSIFIED

22a NAME OF RESPONSIBLE INDIVIDUAL	22b TELEPHONE NUMBER (Include Area Code)	22c OFFICE SYMBOL
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DD FORM 1473, 83 APR EDITION OF 1 JAN 73 IS OBSOLETE.

93 10 1 276

SECURITY CLASSIFICATION OF THIS PAGE

AFOSR Grant No. F49620-92-J-0402 (CIT 64649)

SHOCK PROPAGATION IN CRUSTAL ROCK

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8 September 1993

Annual Report for period 1 July 1992 to 30 June 1993.

Prepared for

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH/PKA
110 Duncan Avenue Suite B115
Bolling AFB DC 20332-0001

OBJECTIVE

The shock Hugoniot and adiabatic release curves of sedimentary rocks display a range of different behaviors that affect the decay of shock waves propagating away form a confined source. Many of the minerals making up sandstones, shales, and limestones undergo phase transitions when shocked to pressures of interest to studies of coupling of energy from explosive sources into far field seismic waves. Both sandstones and limestones have been observed to exhibit elastic precursors and multiple wave behavior at shock velocities up to 3.7 km/s and 5.7 km/s, respectively [*Ahrens and Gregson*, *1964*]. Hysteresis in the shock-release paths of materials results in irreversible energy deposition, thus depriving the shock wave of energy required to drive its propagation and resulting in a more rapid decay and less efficient coupling to far field waves than expected from geometrical effects alone. Thus, data constraining this behavior in rocks are essential for determining the cavity volumes for various degrees of decoupling for different lithologies.

The behavior of most sedimentary rocks during adiabatic release has not been experimentally investigated to a significant extent. Our objective was to obtain experimental data for shock and release behaviors of clastic and carbonate sedimentary rocks and use those data along with data from other sources, to develop a theoretical model of the hysteretic shock-release paths of these rocks. We use this model to constrain the energy deposited irreversibly in these rocks by the passage of shock and release waves. The release model we use is a modification of that used by *Sekine et al.* [*1993*, *submitted*] for granite.

RESEARCH ACCOMPLISHED

We have studied the shock compression and adiabatic release behavior of Coconino sandstone with an initial density $\rho_{0C} = 2.329\ \mathrm{Mg/m^3}$, Solenhofen limestone with initial density $\rho_{0C} = 2.613\ \mathrm{Mg/m^3}$, and a calcareous shale with initial density $\rho_{00} = 2.574\ \mathrm{Mg/m^3}$. The sandstone is essentially quartz with only minor amounts of other constituents and the limestone is essentially pure calcite with very minor amounts of other constituents. The shale, based on a modified CIPW normative mineral calculation, is composed of subequal amounts of quartz, clays, and calcite.

The features of the Coconino sandstone Hugoniot (figure 1) can be identified with those of the quartz Hugoniot. At very low pressures, there is an elastic shock wave which precedes the plastic deformation shock wave. The

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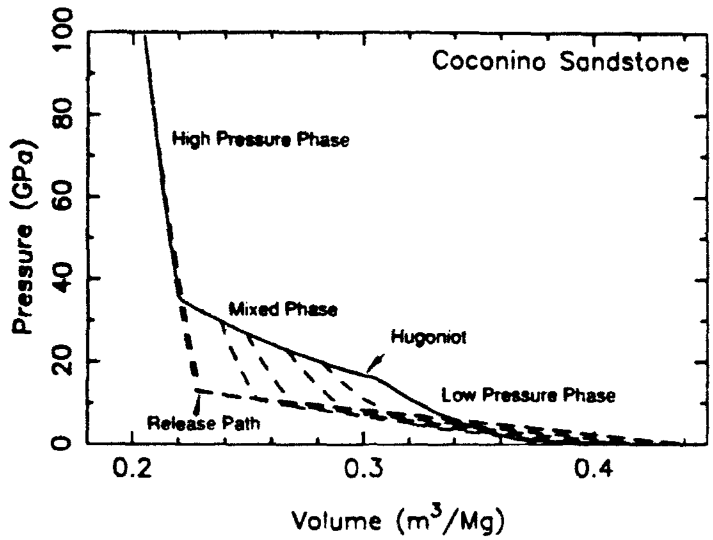

Figure 1. Hugoniot curve and adiabatic release paths for Coconino sandstone.

limiting stress of this elastic wave is the Hugoniot elastic limit (HEL). Above the HEL, the Hugoniot may be broken down into low pressure phase (LPP) and high pressure phase (HPP) stability regions, with an intervening mixed phase (MP) region where insufficient energy is provided by the shock wave to drive the formation of the HPP to completion. Based on the data of *Ahrens and Gregson* [*1964*], the HEL of sandstones seems very strongly dependent on the initial density of the rock. The elastic wave velocity, which has no systematic dependence on strain rate at a given initial density, varies from $2.8\pm.2$ km/s for $\rho_{00} = 1.961$ Mg/m^3 to $3.6\pm.1$ km/s for $\rho_{00} = 2.141$ Mg/m^3.

Above the HEL, the sandstone LPP and HPP can be identified with quartz and stishovite. The sandstone Hugoniot is well modelled using the equation of state (EOS) parameters of quartz for the LPP region and stishovite for the HPP region. The MP region is modelled by a volume weighted average of the HPP and LPP Hugoniot curves in the P-V plane:

$$V_{MP} = fV_{HPP} + (1-f)V_{LPP} \tag{1}$$

where f is the mass fraction of HPP. We assume that f varies linearly with pressure from 0 at the lower bound to the MP region, where HPP formation begins, to 1 at the upper bound of the MP region, where HPP formation is complete. Consideration of the present data and data from *Van Thiel* [*1977*] suggests that HPP formation begins at a Rankine-Hugoniot energy of $E_{RH} \approx 0.95\pm.05$ MJ/kg and is complete at $E_{RH} \approx 3.8\pm.2$ MJ/kg, independent of the initial density of the sample. E_{RH} is given by

$$E_{RH} = \tfrac{1}{2}P_H(V_H - V_{00}) \tag{2}$$

where P_H and V_H are the pressure and specific volume on the Hugoniot and V_{00} is the initial specific volume of the material.

Release adiabats from the LPP region are well modelled by paths which have the same curvature as the nonporous quartz Hugoniot in the P-V plane. We model this behavior by assuming that all release paths from the LPP region of the Hugoniot are isentropes characterized by the same zero pressure bulk modulus, K_{S0}, and its pressure derivative, K_S'. The zero pressure density for a given release path is constrained by the requirement that the isentrope intersect the Hugoniot curve at the proper point. We find Murnaghan equation parameters for these isentropes to be $K_{S0} = 42.7$ GPa and $K_S' = 5.0$.

Release from the HPP region is modelled in a similar fashion, following a curve which mimics the stishovite region of the quartz principal Hugoniot. These isentropes are described by Murnaghan equation parameters $K_{S0} = 377$ GPa and $K_S' = 3.35$. The material follows these curves down to a critical pressure P_c, where the HPP begins to convert to a diaplectic glass with a density of 2.27 Mg/m^3. From P_c to $P = 0$, we assume that the HPP release curve follows a straight line in P-V space to the diaplectic glass volume at zero pressure.

Release from the MP region is modelled as a mixture of the LPP and HPP release paths, according to the prescription in equation (1), with the fraction f of the HPP being frozen at the value achieved on the Hugoniot. Based on the results of *Sekine et al.* [*1993, submitted*], we take P_c to be volume-dependent:

$$P_c = 32.2 - 85.5V \qquad (3)$$

where P_c is in GPa and V is the total specific volume in units of m^3/Mg.

The shale Hugoniot curve (figure 2) also has elastic, LPP, MP, and HPP regions. The HEL of the shale is ~2.35±.15 GPa, corresponding to a shock velocity of 4.7 km/s. The MP region in the shale, based on preliminary results extends from ~15 GPa to ~35 GPa. Taking a nonporous zero-pressure density of $\rho_0 = 2.650$ Mg/m^3 for the shale LPP, we find that the shock wave data can be fit with LPP principal isentrope parameters of $K_{S0} = 33.6$ GPa and $K_S' = 8.5$, under the assumption that the thermodynamic Gruneisen parameter at ρ_0 is $\gamma_0 = 1.0$ and $n = 1$, where

$$\gamma = \gamma_0(\rho_0/\rho)^n \qquad (4)$$

A preliminary model for the HPP based on MP region data and the LPP equation of state and assuming the MP region is modelled by equation (1), is $\rho_0 = 3.172$ Mg/m^3, $K_{S0} = 70$ GPa, $K_S' = 4.0$, and $\gamma_0 = 1.0$ with $n = 1$. The energy of transition, E_{tr}, from low pressure phase to high pressure phase at STP is 0.27 MJ/kg, based on the assumption that the clay minerals are similar to muscovite in that they do not undergo a shock-induced phase transition and that calcite converts to the high pressure phase and quartz converts to stishovite.

Release paths from both the LPP and HPP regions of the shale Hugoniot all fall on or above the Hugoniot, in contrast with the sandstone release paths. We find that release paths from the shale LPP region are well modelled by a suite of isentropes with Murnaghan equation parameters $K_{S0} = 39$ GPa and $K_S' = 6.1$ for release from shock pressures below 14 GPa. Above $P_H = 14$ GPa, the LPP release paths change fundamentally, being better described by a suite of isentropes with $K_{S0} = 31$ GPa and $K_S' = 1$. As with the sandstone LPP and HPP, the zero pressure density for each release path is constrained by the requirement that the release path intersect the Hugoniot at the correct volume. Release paths from the HPP region can be modelled by a suite of isentropes with

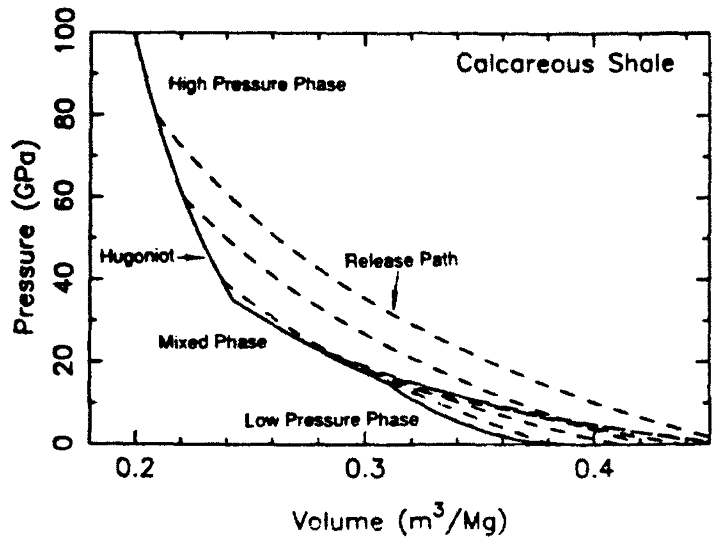

Figure 2. Hugoniot curve and adiabatic release paths for calcareous shale. The large expansions from the low pressure phase region above 14 GPa is also observed in pure carbonates. The release paths above ~50 GPa are not well constrained by the available data.

Murnaghan parameters K_{S0} = 66 GPa and K_S' = 1. Interestingly, the HPP release paths do not show as rapid expansion as the LPP release paths from P_H > 14 GPa. Similar behavior is shown by the release data of *Vizgirda and Ahrens* [*1982*] for aragonite, suggesting that this behavior in the shale can be attributed to the presence of calcite, suggesting that evolution of CO_2 may be important in this region. The MP release paths are well modelled by a mixture of the HPP and LPP release paths according to equation (1), with f frozen at the Hugoniot value.

The limestone Hugoniot is complicated at low pressures by an elastic wave and several phase transitions, causing a multiple wave structure with as many as five separate shock fronts observed in some experiments [*Ahrens and Gregson, 1964*]. The multiple wave structure does not disappear until shock pressures above ~20 GPa, corresponding to a shock wave velocity of ~5.9 km/s, are attained. Above 20 GPa (figure 3), the Hugoniot becomes much less complicated. A single high pressure phase region extends from 31 GPa to over 100 GPa. Based on the results of *Vizgirda and Ahrens* [*1982*], we model this phase with EOS parameters ρ_0 = 3.05 Mg/m^3, K_{S0} = 85.5 GPa, K_S' = 3.75, γ_0 = 1.43, n = 0.6, and E_{tr} = 0.1 MJ/kg. Between 10 GPa and 31 GPa, the final shock state is modelled as a mixture of this high pressure phase and a lower pressure phase that has ρ_0 = 2.985 Mg/m^3, K_{S0} = 110 GPa, K_S' = 4, γ_0 = 1.44, n = 0.6, and E_{tr} = 0. These parameters are not a true equation of state, but provide a convenient estimate of the Hugoniot of the lower pressure phase. As with the mixed phase regions of the shale and sandstone, we model this mixture by equation (1) with the fraction f of the higher pressure phase varying linearly

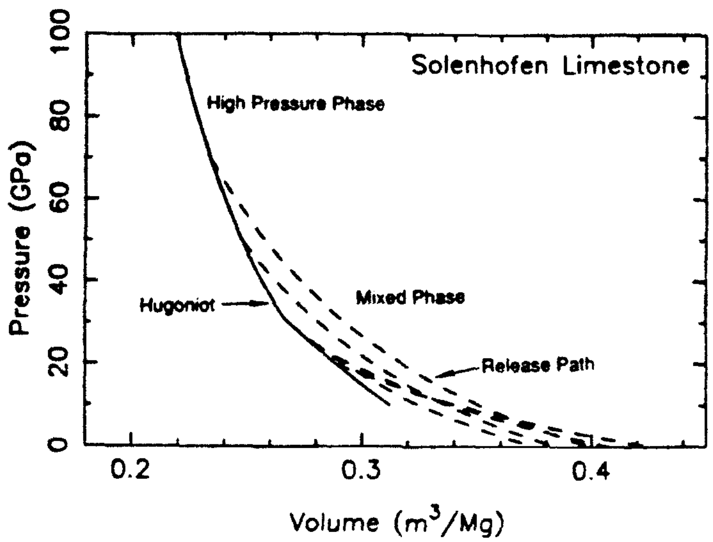

Figure 3. Hugoniot curve and adiabatic release paths for Solenhofen limestone. The shock behavior below 20 GPa is very complicated. The release paths are constrained by the new data obtained in this study and by the data of *Vizgirda and Ahrens* [*1982*].

with pressure between the phase transition onset at 10 GPa and completion at 31 GPa.

Release paths from the single phase region of the Hugoniot are tentatively modelled as isentropes with Murnaghan equation parameters $K_{S0} = 66$ GPa and $K_S' = 2.3$, based on our results and those of *Vizgirda and Ahrens* [*1982*] for aragonite. For the purposes of calculating the mixed phase release paths from Hugoniot states between 14 GPa and 31 GPa, we model the lower pressure phase release paths as isentropes with Murnaghan equation parameters $K_{S0} = 30$ GPa and $K_S' = 1$.

CONCLUSIONS AND RECOMMENDATIONS

We apply the results for the hysteretic shock-release paths of the rocks studied to calculate the fraction f' of the energy E_{RH} that is irreversibly deposited in the material for a given shock pressure using the equation

$$f' = 1 - (E_{Rel}/E_{RH}) \tag{5}$$

where

$$E_{Rel} = \int_{V_R}^{V_H} P dV \tag{6}$$

where the subscripts H and R on V denote the Hugoniot and release volumes, respectively. The resulting estimates for f' are presented in figure 4. For

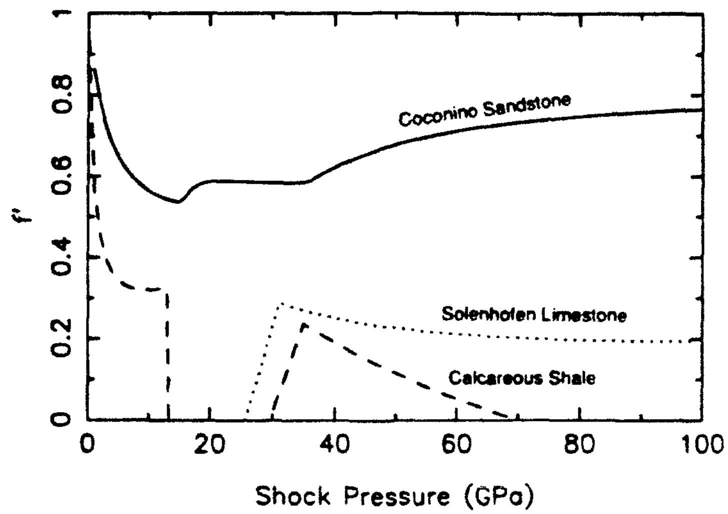

Figure 4. Fraction f' of the Rankine-Hugoniot energy irreversibly deposited in sandstone, shale, and limestone, as a function of shock pressure. The low values for the limestone and shale can apparently be attributed to the release behavior of calcite.

the sandstone, f' approaches 1 at low shock pressures because of pore collapse, but rapidly drops to ~0.53 at 14 GPa, rising slowly thereafter to ~0.77 at 100 GPa. Because the release paths for both the shale and the limestone show large expansions, the value of E_{Rel} is close to E_{RH}. As a result, f' is small for both of these materials, falling below 0.4 for $P_H > 3$ GPa. At shock pressures below ~30 GPa, both shale and limestone show regions where $f' \approx 0$, reflecting the large expansion of calcite on release from the low pressure region of the Hugoniot. The shale shows similar behavior above 70 GPa in the calculations, but this behavior is not well constrained by the data presently in hand. These results suggest that shock waves from sources confined in volatile-rich rocks, especially those rocks rich in carbonates, will decay more slowly (by a factor of ~3) than those in volatile-poor rocks such as sandstones. As a result coupling of explosions is expected to be more efficient in volatile-rich rocks.

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